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Analysis and Normalization of Ceramic/Metal Bi-Element Target Data

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Abstract

The use of semi-infinite, bi-element targets in depth of penetration (DOP) testing initially arose from the need to rank performance of ceramic materials under ballistic impact. Ceramics exhibit complex damage responses. Interpretation of DOP results for ceramic/metal target combinations can be difficult and sometimes misleading. Recent work examined bi-element metal/metal targets to determine additional damage mechanisms present in the earlier DOP ceramic/metal target responses. Significant target interactions were demonstrated in either combination with or in addition to specific damage mechanisms inherent in the ceramic response. The target interactions considered before arose from mismatched densities at the target/target interface. Through an analytical model, the "density" effect and time-dependent mechanisms were separated. The current work, which includes titanium diboride/rolled homogeneous armor (RHA) and titanium diboride/titanium alloy bi-element target designs provides target combinations that are density-matched and strength-matched. The current work presents these new data and provides an analysis to normalize DOP responses for all target combinations. A ceramic damage function that could partially link experimental results to analysis is defined.

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1. Introduction

The depth of penetration (DOP) test method has proven to be a valuable tool for comparative testing and ranking of ceramics. The previous analysis by Rupert and Grace (1993) and Grace and Rupert (1993) has identified a dynamic effect referred to as a "density" effect mechanism for both metallic and ceramic appliques. This analysis demonstrated that evaluation of target materials using DOP testing should take into account the physical phenomena regarding material damage mechanisms and target interaction effects, to include the shock-induced transient and wave reflection from target interfaces. It was concluded that the density of the backup element is responsible for a significant target interaction effect, and this can substantially alter perceived performance. For example, the presence of a higher density second element can reflect pressure waves and associated material flow back toward an approaching penetration. This situation increases penetration rates. A lower density second element creates a reflected tensile wave with material flow away from the penetrator, which reduces penetration rates (Grace and Rupert 1993).

Titanium diboride/rolled homogeneous armor (TiB_2/RHA) and titanium diboride/titanium (TiB_2/Ti) bi-element target designs are used in the current work to examine the normalization of ceramic DOP data. The particular materials selected allowed sets of density-matched and strength-matched bi-element target combinations to be considered. The experimental data are presented together with an analysis of the mechanisms acting in the penetration of these materials.

2. Materials

2.1 Steel. Standard U.S. Army practice measures armor performance in terms of mass- and space-efficiency factors, E_m and E_s, defined in terms of a reference steel (e.g., RHA [Frank 1981]). Military specifications for the manufacturing process and material properties of RHA are described in MIL-A-12560G (MR) (U.S. Army Materials and Mechanics Research Center [AMMRC] 1984). Typical room-temperature property data for RHA were measured from random 100- to 152-mm RHA plates used at the U.S. Army Research Laboratory (ARL) and are listed in Table 1. Large

Table 1. Property Data

Property	RHA Steel, MIL-A-12560	Ti, 6Al/4V	TiB_2[a]
Density (g/cm^3)	7.85	4.45	4.48
Hardness (BHN)	241–375	302–340	2,700 (kg/mm^2)[b]
Average Grain Size (µm)	NA[c]	NA	15
Compressive Strength (GPa)	NA	NA	4.82
Tensile Strength (MPa)	793–1,172	896–910	NA
Yield Strength (MPa)	655–1,055	827–862	NA
Elongation	8–20%	10–12%	NA
Young's Modulus (GPa)	207	113.8	556
Poisson's Ratio	0.29	0.342	0.11
Sonic Velocity:			
Longitudinal (m/s)	5,876	6,070	11,285
Transverse (m/s)	3,196	2,974	7,431

[a] CERCOM, Inc.
[b] Knoop 300 g.
[c] Not available.

variations in the property data for the RHA are the result of MIL-A-12560 being a performance-based specification. As a result, chemical composition, heat treatments, and physical properties vary greatly between vendors. Physical properties also vary with plate thickness. To minimize the effects that these variations have on ballistic performance, targets were fabricated from a single thickness of plates from the same vendor and same heat.

2.2 Titanium. With the recent reduction in the cost of Ti alloys, there is a renewed interest in using Ti as an armor material. Property data for armor plates used in the recent evaluation of low-cost Ti-6Al-4V plates and this study are listed in Table 1 (Burkins, Hansen, and Paige 1994). Ti alloy was selected for this study, since its strength and sound velocity are similar to those of RHA.

2.3 Titanium Diboride. A high-purity armor grade TiB_2 manufactured by CERCOM Incorporated, Vista, CA, was used in this study. These tiles were nominally 101.6 mm square with thickness ranging from 6.35 mm to 35 mm. Selection of this ceramic was based on two factors.

First, the TiB_2 has a density similar to that of the Ti alloy. Second, the TiB_2 has an acoustic impedance (product of density and sound velocity) close to that of the RHA. Additional property data for the ceramic files used in this study are listed in Table 1.

3. Test Procedures

3.1 DOP Testing. DOP testing was developed as a means of ranking ceramic materials for ballistic applications by various groups, including Woolsey, Mariano, and Kokidko (1989), Alme and Bless (1989), Bless, Rosenberger, and Yoon (1987); and Woolsey, Kokidko, and Mariano (1990). Performance is measured by the DOP of a long-rod penetrator into a semi-infinite steel backplate after passing through a ceramic applique. Ceramic performance comparisons are then made between selected baseline materials using performance maps, as illustrated in Figure 1. Woolsey identified four performance regions, based on the general appearance of the data when plotted. Region I is where little or no reduction in penetrator performance occurred in the rear element after perforating thin ceramic appliques. Region II is where a marked reduction in penetration occurred with increased ceramic thickness. Region III is where a gradual reduction in penetration into the rear element occurred with increased ceramic thickness. Region IV is where the ceramic reached a critical thickness where penetration into the second element abruptly stopped.

Further work by Grace and Rupert (1993) provided physical explanations for the four regions. Region I was defined as the region where the dynamic target interaction or "density" effect is the dominate factor for thin ceramic sections. This region is characterized by a reduced penetrator erosion rate and a consequent increased penetration rate. The transient, which exhibits a higher penetration rate for a penetration depth of about a rod diameter, affects a larger portion of the total penetration of the ceramic applique in this region. Further, a proximate boundary of relatively higher density second element can reflect pressure waves and associated material back toward the approaching penetrator, also increasing the penetration rate.

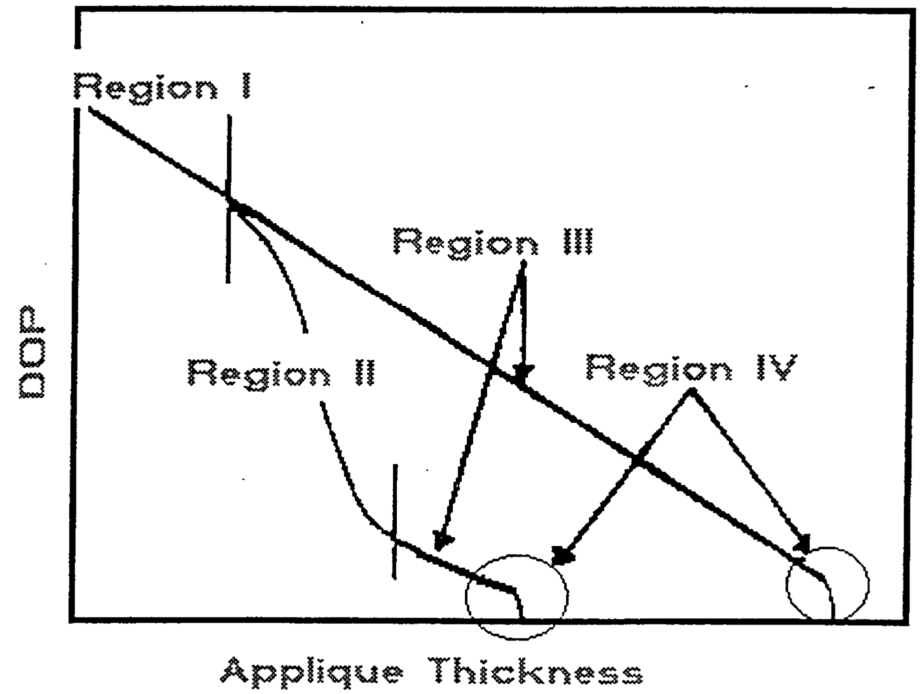

Figure 1. Generalized Performance Map.

Region II is the region where time-dependent damage mechanisms, resulting in a mixed solid/granular flow, and the rate of transition from this flow to pure granular flow are dominant. As the ceramic first element becomes thicker, the transient affects a smaller portion of the total penetration of the ceramic. Also, the strength of the "density" affects decreases with ceramic thickness (Grace and Rupert 1993). Both of these effects result in an increased penetrator erosion rate and consequent decreased penetration rate. However, this is countered by the time-dependent strength loss of the ceramic as it transitions to granular flow.

Region III is defined as a region where pure granular flow becomes more dominant in the penetration of the ceramic. Rigid-body penetration of the damaged ceramic may also occur in this region. Region IV is the termination phase, where the unconsumed rod traveling at low velocity abruptly decelerates and stops. This type of testing has been extended to include bi-element metallic targets in the cited prior work.

3.2 Projectiles. The tungsten heavy alloy (WHA) projectile used in this study was the 65-g, 93% W-4.91% Ni-/2.11% Fe long-rod penetrator manufactured by Teledyne Firth Sterling. The penetrator was produced using the nominal X-21 process with 25% swaging. The penetrator had a diameter of 7.82 mm, an L/D ratio of 10, and a hemispherical nose. Nominal material properties for these penetrators are as follows: density was 17.6 g/cm^3, hardness was Hardness Rockwell C Scale 40.5–42.6, yield strength was 1.09–1.17 GPa, ultimate strength was 1.13–1.21 GPa, and elongation was 5.8–10.6% (Teledyne Firth Sterling 1991; Farrand 1991).

3.3 Range Setup. The penetrators were fired from a laboratory gun consisting of a Bofors' 40-mm gun breech assembly with a custom-made 40-mm smoothbore barrel. The gun was positioned approximately 3 m in front of the targets. High-speed (flash) radiography was used to record and measure projectile pitch and velocity. Two pairs of orthogonal x-ray tubes were positioned in the vertical and horizontal planes along the shot line (as illustrated in Figure 2). Propellant weight was adjusted for the desired nominal velocity of 1,500 m/s. Projectiles with a striking total yaw in excess of 2° were considered a "no test," and those data were disregarded.

3.4 Target Construction. TiB_2 DOP target construction followed general features of the standard design, as shown in Figure 3 (Woolsey, Mariano, and Kokidko 1989; Woolsey, Kokidko, and Mariano 1990). For the targets used here, no aluminum foil was used, but, rather, the ceramic tile was glued directly to the RHA backing plate. Targets shot in this test series consisted of 101.6-mm (4 in)-square ceramic tile, instead of the 152.4-mm (6 in)-square ceramic tile, as shown in Figure 3. The ceramic tile was held into a steel lateral confinement frame by EPON 828 and VERSAMID 140, with a mixing ratio of 1:1, and a nominal thickness of 0.5 mm. The frame had a 19-mm (3/4 in) web and a depth equal to or greater than the tile thickness. The frame was mechanically secured to a thick steel backup plate. This steel backup plate was made from a single RHA steel, MIL-A-12560, Class 3, 127 mm (5 in) thick, with a nominal hardness of R_c 27. A 102-mm (4 in)-thick Ti-6Al-4V plate was substituted for the 127-mm RHA plate in targets requiring a Ti second element.

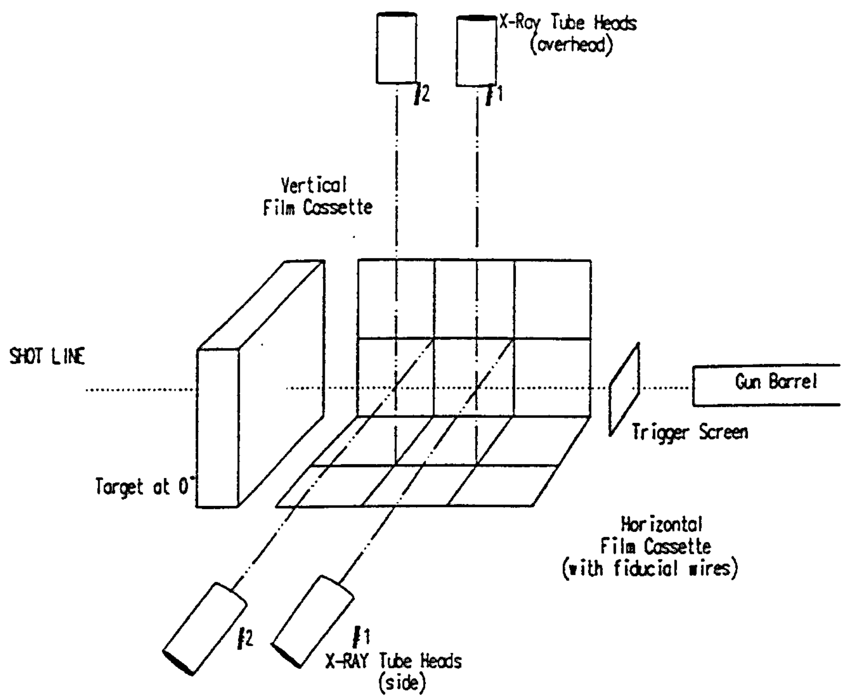

Figure 2. Test Setup.

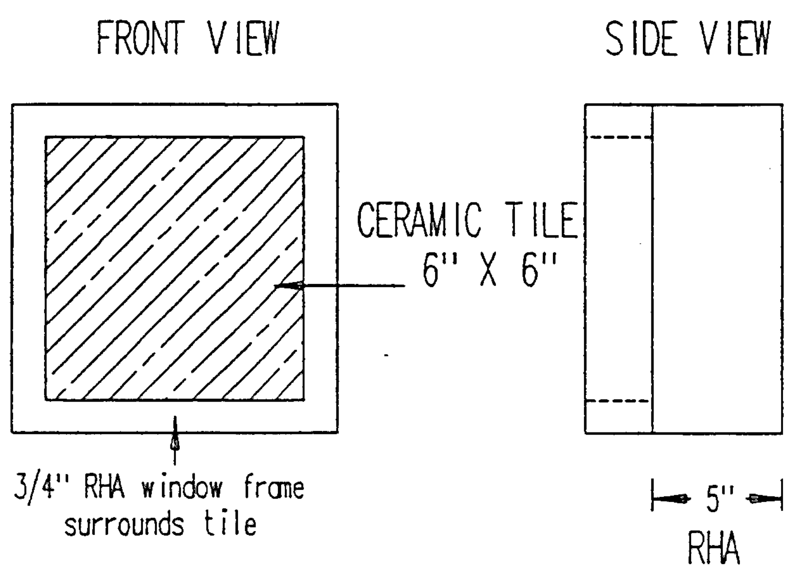

Figure 3. DOP Ceramic Target.

4. Experimental Results

4.1 Penetration Into Monolithic RHA Steel. Penetration data against semi-infinite (152 mm thick), monolithic RHA targets for the 93% WHA penetrator used are available over a wide range of velocities, from 800 m/s to 1,750 m/s (Woolsey, Kokidko, and Mariano 1990). Over this range of interest, the data are linear. Thus, a linear empirical fit to the penetration data was derived for RHA steel. The resulting equation is as follows:

$$DOP_{(RHA)} = 0.0833 \left(\frac{mm \cdot s}{m} \right) V_s - 55.88\ mm\,, \qquad (1)$$

where V_s is the striking velocity in meters per second, while DOP and the right-hand constant are in millimeters. To correct for variations in the actual striking velocities, all residual penetration values for ceramic and metallic bi-element targets with RHA second elements were adjusted to a striking velocity of 1,500 m/s by the following correction based on equation (1):

$$DOP' = \text{Measured DOP} + 0.0833 \left(\frac{mm \cdot s}{m} \right) (1{,}500\ m/s - V_s)\,, \qquad (2)$$

where, again, the units are meters per second and millimeters. This technique is considered uniformly valid for different materials, when a significant amount of the rod length, and therefore penetration, occurs in the RHA steel backplate (Woolsey, Kokidko, and Mariano 1990).

4.2 Penetration Into Monolithic Titanium. Penetration data for the 93% WHA penetrator against monolithic Ti-6Al-4V are based on five tests, wherein striking velocity ranged from 1,079 m/s to 1,672 m/s against semi-infinite (two, 102 mm thick) plates (Burkins, Hansen, and Paige 1994). Over this range, the data are linear; an empirical fit to the data was derived. The resulting equation is as follows:

$$\mathrm{DOP}_{(\mathrm{Ti})} = 0.108 \left(\frac{\mathrm{mm} \cdot \mathrm{s}}{\mathrm{m}} \right) V_s - 81.7\,\mathrm{mm}\,, \tag{3}$$

where V_s is the striking velocity in meters per second, and the DOP and constant are in millimeters. To correct for variations in the actual striking velocities, all residual penetration values for metallic bi-element targets with Ti alloy second elements were normalized to a striking velocity of 1,500 m/s by the following correction, based on equation (3):

$$\mathrm{DOP}' = \text{Measured DOP} + 0.108 \left(\frac{\mathrm{mm} \cdot \mathrm{s}}{\mathrm{m}} \right) (1{,}500\,\mathrm{m/s} - V_s)\,, \tag{4}$$

where, again, the units are meters per second and millimeters.

4.3 Penetration Into Titanium Diboride/Titanium and Titanium Diboride/RHA. DOP′ results for TiB_2/Ti and TiB_2/RHA targets (15 each) are shown in Figures 4 and 5 and listed in the appendix. The open triangles in Figure 4 plot the individual data points for the TiB_2/Ti bi-element targets. The solid triangle represents the semi-infinite DOP for Ti, based on equation (3). The open diamonds in Figure 5 provide individual data points for the TiB_2/RHA. The open diamond represents a semi-infinite RHA target. The solid diamond represents the semi-infinite DOP datum point for RHA, based on equation (1). Corrections for striking velocity variations were generally less than 2 mm for the current data set using equations (2) and (4).

5. Analysis and Discussion

The experimental results show both similarities and contrasting differences to the prior behavior as depicted in DOP performance maps. A typical map, including lower and upper performance envelopes for Al_2O_3/AD995 CAP3/RHA target systems against a 65-g, depleted uranium (U-3/4 Ti), hemispherical nose penetrator at 1,500 m/s, is shown in Figure 6 (lines 2 and 3) (Grace and Rupert 1993). Target construction for the Al_2O_3/RHA targets was similar to that used in the current study.

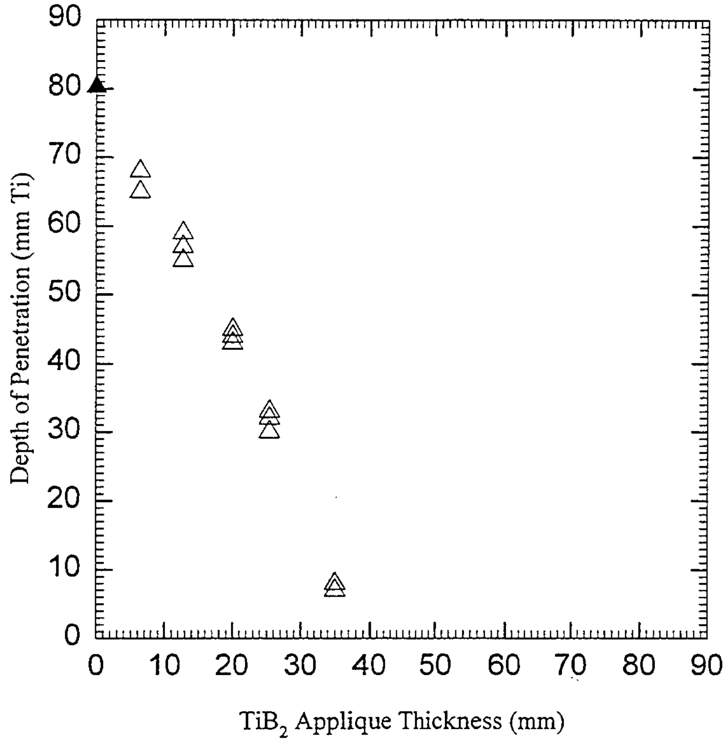

Figure 4. DOP Results for TiB$_2$/Ti.

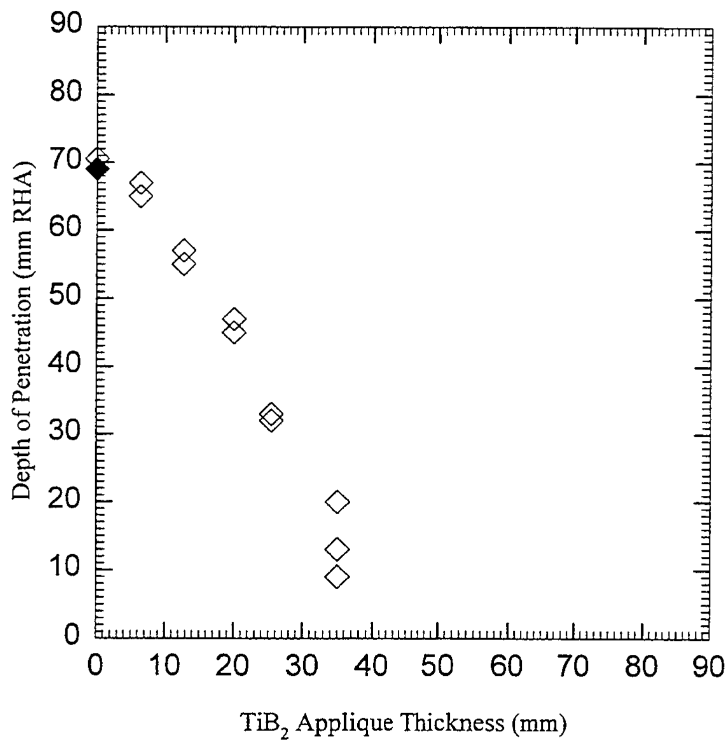

Figure 5. DOP Results for TiB$_2$/RHA.

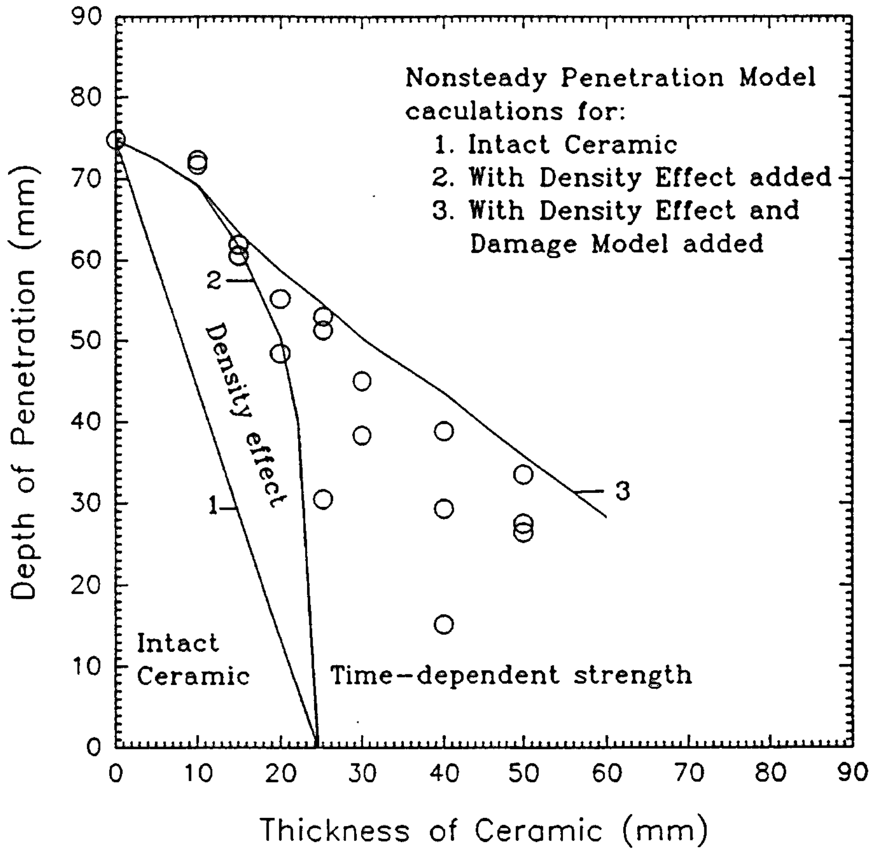

Figure 6. Model Results for Al_2O_3/RHA.

For the data presented in Figures 4 and 5, one striking difference is the relatively small amounts of scatter in the TiB_2 data, which may reflect consistency in these particular ceramic tiles and in target construction. A second difference is that the TiB_2/RHA system shows the performance shift relative to the rule of mixtures associated with Region I, whereas the TiB_2/Ti alloy system does not contain a shift in performance relative to the rule of mixtures. The rule of mixtures was based on the assumption that there is no interaction between the material and that total penetration is the sum of the two materials. Thus, the bi-element target performance is the sum of the proportional performances of the constituent target materials. While the shock-impedence equation was used previously (Grace and Rupert 1993) to provide a form for the density effect, the current target systems indicate that results do not correlate with impedence, but rather with density. Thus, the previous form can be taken, at this point, as empiric. The appearance or absence of a shift relative to the rule of mixtures has been analyzed previously by the authors (Rupert and Grace 1993; Grace

and Rupert 1993) and found to depend on a density effect associated with the order of densities within the bi-element target arrangement.

As a result, the performance of both systems fits the density effect analysis. Consequently, no shift in the TiB_2/Ti system was expected. The TiB_2 ceramic appears to have lower performance when backed by RHA in contrast to its relatively high performance when backed by Ti alloy, even in thin sections (<20 mm). With the density effect analysis, it is believed that the TiB_2 maintains its nominal strength in Region I in either case, but becomes subject to time-dependent damage (strength loss) with increased ceramic thickness as the performance extends into Region II. Both data sets show that with increased ceramic thickness, Region II performance is maintained, as would be expected, based on either the full nominal strength of the ceramic or an initial transition into damage within the ceramic. Further performance losses, characteristic of Region III, wherein the process is dominated by granular flow, are absent.

The DOP data were analyzed further by introducing a more extensive normalization of the data by equation (5). Reference materials for this normalization were Coors' AD-995 Al_2O_3 CAP 3 ceramic in the first element and RHA in the second element. Factors for the normalization are defined as follows.

a_N	- Normalized thickness of first element in terms of a reference first element (mm)
a_o	- Thickness of first element (mm)
c_{RSW}	- Rayleigh wave/shear wave velocity for ceramic damage model (m/s)
DOP_N	- Normalized DOP results in terms of two reference materials (mm)
DOP'	- Velocity-corrected DOP results (mm)
P_{DE}	- Penetration shift due to density effect (mm)
$P_{S(Al_2O_3)}$	- Undamaged semi-infinite Al_2O_3 AD-995 CAP 3 penetration value, based on theoretical calculations (mm)
$P_{S(RHA)}$	- Semi-infinite RHA penetration value from experimental data or theoretical calculations (mm)

P_{S1} - Semi-infinite penetration value for undamaged first element material, based on theoretical calculations (mm)

P_{S2} - Semi-infinite second element material penetration value from experimental data or theoretical calculations (mm)

$\acute{\eta}$ - Damage growth rate coefficient (s^{-1})

The first factor in equation (5a) subtracts out the target interaction effect contained in Region I. This factor is represented as (DOP′ - P_{DE}), where P_{DE} is the shift along the ordinate due to the density effect as calculated using the analysis of Grace and Rupert (1993). In addition, the shifted DOP results are multiplied by the ratio of semi-infinite penetration for RHA relative to the second element. The ceramic thickness along the abscissa is adjusted by a factor to reflect differences in semi-infinite penetration into the first element when compared to that of Al_2O_3. Further, to incorporate the time-dependent damage effects within Region II, a damage function is introduced as an additional adjustment to the depth of penetration. This factor reflects any slope changes associated with higher or lower rates of damage in the ceramic material. The preceding factors result in the following equations for a normalized lower performance limit DOP_N:

$$DOP_N = \frac{P_{S(RHA)}}{P_{S2}} \left(DOP' - P_{DE} \right) - \frac{P_{S1}\, P^2_{S(RHA)}}{P_{S2}\, P_{S(Al_2O_3)}} \int_0^{a_o} f\left(c_{RSW}, a_o, \acute{\eta}\right) da, \qquad (5a)$$

$$a_N = a_o \frac{P_{S(Al_2O_3)}}{P_{S1}}. \qquad (5b)$$

Transition between penetrator materials may be accomplished by defining DOP′, P_{DE}, P_{S1}, and P_{S2}, performance in terms of the nonreference penetrator material.

It should be noted that $f(c_{RSW}, a_o, \acute{\eta}) = 0$ for metal/metal targets or ceramic/metal targets where the ceramic tiles exhibit its intact nominal strength throughout the penetration process. Estimates for $P_S(Al_2O_3)$ and P_{S1} were obtained using intact strengths of 2.0 GPa (Al_2O_3) and 2.78 GPa (TiB_2)

in a one-dimensional penetration model (Grace 1993). The values were $P_S(Al_2O_3) = 22.71$ mm and $P_{S1} = 12.73$ mm. For material that exhibits time-dependent damage, the $f(c_{RSW}, a_o, \dot{\eta})$ can be determined from the data graphically or calculated by suitable damage models (Cortés et al. 1992; Corran et al. 1993) or by Grace and Rupert (1993). The normalization in equation (5) with the defined $f(c_{RSW}, a_o, \dot{\eta})$ permits a convenient framework through which various factors affecting damage growth rates can be examined. Further, the function should account for all influencing factors to include statistical property variations within the ceramic, as related to the time-dependent damage, such as flaw densities, flaw orientation, etc., as well.

In Figure 7, lower performance limits (upper data points) are presented for TiB_2/RHA, TiB_2/Ti alloy, and Al_2O_3/RHA. The data for Al_2O_3 thickness have been normalized by the ratio of its density to that of TiB_2 (abscissa). The TiB_2/RHA, TiB_2/Ti alloy, and Al_2O_3/RHA DOP results have been normalized and presented as percent of the semi-infinite penetration for the second element (ordinate). Both TiB_2/RHA and Al_2O_3/RHA systems show the characteristic shift of Region I for the thin ceramic appliques. Further, the slopes of TiB_2/RHA and TiB_2/Ti alloy are similar in Region II, indicating that the time-dependent strength and damage growth rate of the TiB_2 applique may be independent of the backing material so long as sufficient support is provided. The lower slope for the Al_2O_3/RHA may reflect the effects of its lower nominal strength relative to TiB_2, and/or a higher time-dependent damage growth rate relative to TiB_2 on the penetration process. The nominal intact strength used in the modeling (undamaged ceramic strength) was found to correlate well with the shear component of the compressive strength (Grace and Rupert 1993). Thus, intact strengths used in the modeling here were 2.0 GPa (Grace and Rupert 1993) for Al_2O_3 and 2.78 GPa for TiB_2. The change in curvature of the Al_2O_3 line, representing the lower performance limit at large thickness, suggests a transition toward the higher damage states associated with Region III (pure granular flow).

In Figure 8, ceramic data from the present work are plotted together with the Al_2O_3 lower performance limit curve, and the metal/metal response data (Rupert and Grace 1993), using the normalization process of equation (5) without the damage function correction. The normalization places all of the metal/metal data on the same curve by subtracting out the shift in DOP response for the Ti/RHA target. Further, when all major factors considered in the penetration process are

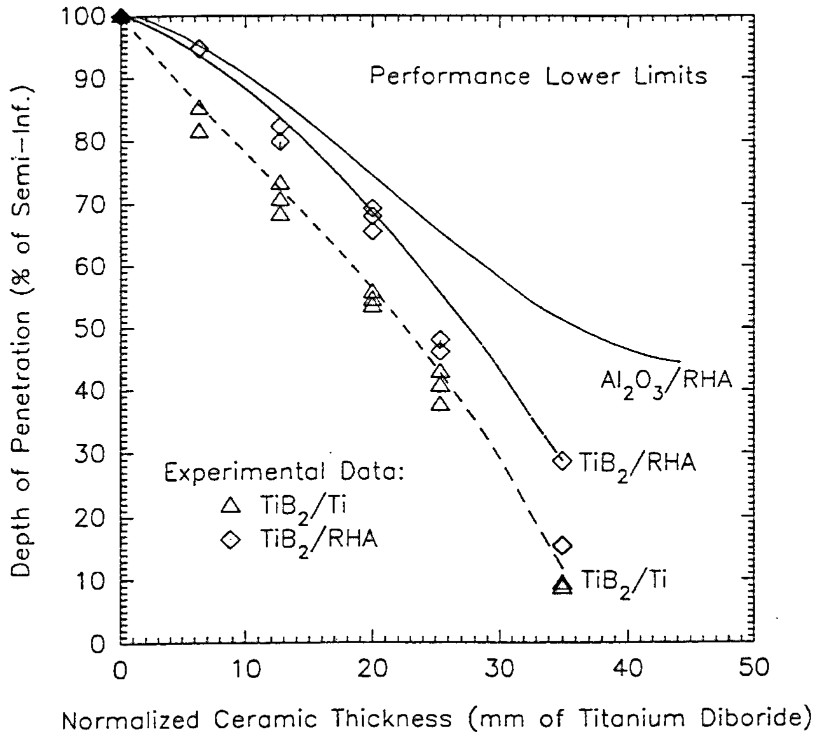

Figure 7. Normalized Data Plot.

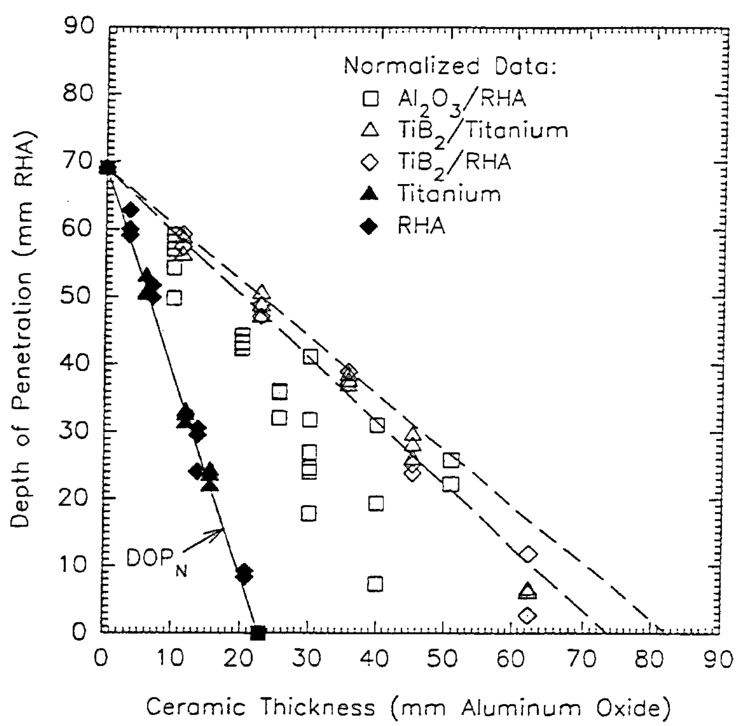

Figure 8. Partially Normalized DOP_N Results.

normalized, except for $f(c_{RSW}, a_o, \acute{\eta})$, the lower performance limits of the two ceramics are not much different. This result suggests that the factors within the function combine so that the overall time-dependent strength loss and its effect on the DOP are approximately equal on a normalized basis for these particular ceramic materials. From Figure 8, the average damage function value for both ceramics is estimated to be 1.47-mm RHA per millimeter Al_2O_3. This value was estimated by taking the difference of the slopes between the DOP_N curve and a least-square fit of the ceramic data as plotted in Figure 8. However, the lower performance limits may be more useful for armor designs. Damage function values based on these limits are 1.35- and 1.16-mm RHA per millimeter Al_2O_3 for Al_2O_3 and TiB_2, respectively. When the damage function is taken into account in equation (5), the ceramic data can be further normalized so that all DOP response points would lie near the single curve given by the data points for the metal targets. Thus, the damage function has been isolated from the various other contributing factors important to the penetration process. Research in the future can address the specific nature of the damage function.

6. Summary

In this work, DOP responses of TiB_2/RHA and TiB_2/Ti alloy bi-element targets were determined and contrasted to the general ceramic behavior in DOP performance maps. The TiB_2 ceramic performed very well in thin sections (elemental mass efficiencies of 3.0+) when backed by Ti alloy, demonstrating high ceramic strength. Although the TiB_2/RHA targets did not perform as well as the TiB_2/Ti alloy systems in thin ceramic sections (elemental mass efficiencies of 1.0), the difference was due to a target/target interaction during penetration, or density effect, as a result of density order of the bi-element targets rather than loss of ceramic strength. Lower performance bounds for the TiB_2 and a baseline Al_2O_3 ceramic show that the density effect is present in these systems. These results are consistent with prior findings regarding Al_2O_3/RHA responses (Grace and Rupert 1993). The present analysis was able to separate the overall mechanical response of the penetration process from that which involves time-dependent damage response (strength losses) in the ceramic during penetration. The normalization equation includes the separation of factors and defines a damage function to be determined experimentally or analytically. The model, including the isolated damage function, provides direction for future research efforts.

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Appendix:

Firing Data

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Table A-1. Depth of Penetration (DOP) Results for TiB_2/RHA

Applique Thickness (mm)	Striking Velocity (m/s)	Pitch (deg)	Yaw (deg)	DOP (mm)	Corrected DOP (mm)
6.35	1,521	0.00	0.00	69	67
6.35	1,509	0.00	0.00	66	65
6.35	1,507	0.75 U	0.75 R	66	65
12.70	1,511	0.25 U	0.50 R	56	55
12.70	1,499	0.50 U	0.50 L	55	55
12.70	1,502	0.50 U	0.25 L	57	57
20.00	1,510	0.00	0.00	46	45
20.00	1,501	0.00	0.00	47	47
20.00	1,503	0.25 U	0.25 L	47	47
25.40	1,502	0.00	0.00	32	32
25.40	1,499	0.50 U	0.00	33	33
25.40	1,511	0.25 D	0.50 L	34	33
35.00	1,502	0.50 D	0.00	20	20
35.00	1,491	0.50 D	0.00	12	13
35.00	1,517	0.00	0.75 L	10	9

Table A-2. Depth of Penetration (DOP) Results for TiB_2/Ti

Applique Thickness (mm)	Striking Velocity (m/s)	Pitch (deg)	Yaw (deg)	DOP (mm)	Corrected DOP (mm)
6.35	1,450	1.50 D	1.00 R	60	65
6.35	1,525	0.25 D	0.50 L	71	68
6.35	1,497	0.50 U	0.00	65	65
12.70	1,503	0.50 U	0.25 R	59	59
12.70	1,512	0.50 U	0.25 L	56	55
12.70	1,513	0.75 U	0.25 R	58	57
20.00	1,502	0.00	0.50 R	43	43
20.00	1,494	0.75 D	0.00	44	45
20.00	1,485	0.75 D	0.25 L	42	44
25.40	1,499	0.00	0.75 L	30	30
25.40	1,460	0.25 U	0.00	28	32
25.40	1,486	0.25 D	0.50 L	31	33
35.00	1,519	0.25 D	0.25 L	9	7
35.00	1,495	0.00	0.50 L	7	8
35.00	1,500	0.25 U	0.00	7	7

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13. ABSTRACT *(Maximum 200 words)*

The use of semi-infinite, bi-element targets in depth of penetration (DOP) testing initially arose from the need to rank performance of ceramic materials under ballistic impact. Ceramics exhibit complex damage responses. Interpretation of DOP results for ceramic/metal target combinations can be difficult and sometimes misleading. Recent work examined bi-element metal/metal targets to determine additional damage mechanisms present in the earlier DOP ceramic/metal target responses. Significant target interactions were demonstrated in either combination with or in addition to specific damage mechanisms inherent in the ceramic response. The target interactions considered before arose from mismatched densities at the target/target interface. Through an analytical model, the "density" effect and time-dependent mechanisms were separated. The current work, which includes titanium diboride/rolled homogeneous armor (RHA) and titanium diboride/titanium alloy bi-element target designs provides target combinations that are density-matched and strength-matched. The current work presents these new data and provides an analysis to normalize DOP responses for all target combinations. A ceramic damage function that could partially link experimental results to analysis is defined.

14. SUBJECT TERMS

ceramics, bi-element, density effect, normalization

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